

UTILIZATION OF COAL-DERIVED LIQUID FUELS IN A COMBUSTION TURBINE ENGINE

A. V. Cabal, M. J. Dabkowski, R. H. Heck, T. R. Stein
Mobil Research and Development Corporation, Paulsboro, New Jersey

R. M. Chamberlin, P. R. Mulik, P. P. Singh
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

W. C. Rovesti
Electric Power Research Institute, Palo Alto, California

1.0 INTRODUCTION

A number of processes are currently being developed on a large scale to produce liquid fuels from coal(1). It is anticipated that these coal liquids will supplement the ever decreasing supplies of petroleum crude now refined to produce gasoline, distillates, and residual fuel oil. However, detailed analysis of these coal liquids shows that they are more aromatic and contain more nitrogen and oxygen than do corresponding fractions from petroleum(2,3). In addition, coal liquids containing residual fractions high in asphaltenes, are incompatible when blended with typical petroleum fuels(4). Some preliminary results have been reported on the combustion of heavy coal liquids in residential boilers(5) and of synthetic jet fuel in aviation turbines(6).

The purpose of this work was to evaluate the use of raw and hydrotreated heavy distillate coal liquids from the Solvent Refined Coal (SRC) and H-Coal processes for use in heavy duty utility turbines. Presently, these turbines account for about nine percent of the installed power generation capacity in the U.S. Most of this capacity is dedicated to peak load generation where high reliability and the ability to put the capacity on-line rapidly are of critical importance. In the future, gas turbine capacity is expected to grow for intermediate and base load as high temperature combined cycle systems are introduced for power generation.

In considering fuels for use in these plants, certain fundamental combustion properties must be established in order to assure safe, efficient, and clean combustion of these fuels. Reliable utilization includes the determination of the operating limits of the combustion turbine with respect to corrosion, erosion, and deposition. Dependable operation of the combustor without the occurrence of flame-out, fouling or overheating of the combustor basket is also required for safe operation on coal-derived fuels. Furthermore, the time and power lost during shutdown to clean or repair hardware is an important factor to be considered. Finally, emissions from turbines burning coal-derived liquids must meet projected stringent EPA standards for oxides of sulfur and nitrogen.

Distillate coal liquids from the H-Coal and SRC processes were evaluated in a laboratory turbine combustor passage. The test fuels consisted of raw coal liquids and the same liquids hydroprocessed at several severity levels to produce additional test fuels of varying aromatic and nitrogen content. Each fuel was characterized by physical, chemical, and compositional analyses, and was evaluated in a small laboratory combustor at simulated commercial turbine

conditions. It should be noted here that due to the limited fuel quantity available, flows in this combustor were approximately 300 times smaller than those in full scale engines, so that caution should be exercised in interpreting the trends detected.

2.0 EXPERIMENTAL

2.1 HYDROPROCESSING OF COAL LIQUIDS

Samples of distillate coal liquids from the SRC pilot plant in Wilsonville, Alabama, and the H-Coal pilot plant in Trenton, New Jersey, were hydrotreated in a fixed-bed hydroprocessing pilot unit of the Mobil Research and Development Corporation. Commercial nickel-molybdenum and cobalt-molybdenum catalysts were employed for the H-Coal and SRC samples respectively. Each liquid was hydroprocessed at several sets of processing conditions. SRC recycle solvent processed at three different severities and H-Coal distillate processed at two different severities were selected for the tests. The entire liquid product was utilized for the SRC liquid, while the product from the H-Coal distillate was distilled to obtain a 350°F+ sample for the turbine tests.

Five gallons of each of the raw coal liquids, two gallons of each of the SRC hydrotreated liquids and three gallons each of the hydrotreated H-Coal liquids were sent to the Westinghouse Research Laboratories in Pittsburgh for testing in the small scale turbine combustor.

2.2 COMBUSTION TESTS

In order to evaluate the effect of burning coal-derived liquid fuels in commercial combustion turbines, it was necessary to reproduce as accurately as possible the gas residence time, temperature and aerodynamics of a combustor operating on conventional fuels. Because of the limited quantities of coal liquids available for these tests, a subscale combustor was designed and its performance evaluated on No. 2 distillate fuel to demonstrate combustion and emission characteristics representative of full scale combustors. Tests were performed at fuel flow rates of 1.6 gph with nominal operating conditions fixed as follows:

Combustion air pressure	3.0 atm
Combustion air temperature	500°F
Combustion air flow	0.1 lbs/sec
Fuel pressure	100 psig
Fuel flow	1.6 gph
Atomizing air pressure	70 psig
Atomizing air flow	3-5% of fuel flow
Reference velocity	7 ft/sec
Combustor exit temperature	1800°F
Primary zone residence time	~0.05 sec
Heat release rate	~1200 BTU/sec ft ³
Combustor cooling air flow	~40% total air
Diluent air flow	~20% total air
Combustor pressure drop	~3% of inlet pressure

The combustion test passage is shown in Figure 1. A bank of rotary compressors supplies compressed air, through an indirectly fired preheater, to the test passage. This system is designed to deliver 6.5 lb/sec of air at a pressure of 6 atm and a maximum temperature of 800°F. The desired quantity of combustion air is metered by a sharp edged orifice and forwarded to the combustor while the remaining air is bypassed and ultimately dumped near the end of the test passage. The test fuel is burned in a four-inch diameter combustor and the resultant hot gas flows through the passage past a back pressure valve which is partially closed to maintain a set pressure in the test passage. Thermocouples mounted on the combustor are used to measure and monitor the combustor wall temperature. Two thermocouples are placed directly after the combustor to measure the temperature of the hot combustion products. The exhaust products are then passed through a mixing device and an array of six thermocouples measures the mean bulk exhaust temperature of the gases. The temperatures of the thermocouples are recorded on a twenty-four point recorder. Further downstream, provisions exist for mounting test pins and for procuring samples of the exhaust gas for both emission analyses and smoke number determinations. A much larger sample flow rate than necessary is used to minimize sampling line interference and keep the residence time small. The sample gas is dried and filtered and passed to various analyzers.

In a typical run the combustion test passage was first fired with No. 2 fuel and allowed to run until the set standard test conditions were reached. The item with the longest time constant was the air preheater. It generally took about an hour before the combustion air temperature was up to the test design point. When the required combustion air temperature was reached the air flow through and the pressure in the combustion test passage was set at the desired level. The fuel flow was set to give an exhaust mixed temperature of approximately 1800°F. The combustion test passage was run until steady-state conditions were achieved and the base-line data for No. 2 fuel was obtained. Smoke Numbers, CO₂, CO, NO_x and unburned hydrocarbon levels in the exhaust were measured. A two color pyrometer was sighted through a view port to obtain the flame temperature in the primary zone.

By slowly turning off the No. 2 fuel oil needle valve and turning on the coal-derived liquid fuel valve a switchover with a negligible excursion from the set test condition was obtained. When the transition was complete, data were taken every fifteen minutes.

3.0 RESULTS AND DISCUSSION

3.1 HYDROPROCESSING RESULTS

The SRC recycle solvent was hydroprocessed over a commercial CoMo/Al₂O₃ catalyst (Cyanamid HDS-1441A) at three severity levels while the H-Coal distillate was hydroprocessed over a commercial NiMo/Al₂O₃ catalyst (Ketten 153S) at two severity levels. Table 1 lists the properties of the feeds and hydroprocessed liquid products from these runs. Also shown in Table 1 are the processing conditions, yields of all products, and degree of heteroatom (O, N, S) removal. For the SRC recycle solvent, the pressure was held constant at 2500 psig for all three runs. The two highest severity runs were made at 715°F and space velocities of 0.8 and 0.4 consuming 2260 and 2800 SCF H₂/Bbl respectively. For the lowest severity run, the temperature was decreased to 678°F and the space

velocity increased to 2.9 LHSV. This resulted in a hydrogen consumption of 1140 SCF/Bbl. In all cases, the yield of C₆+ liquid product was greater than 98 %. The sulfur removal was greater than 85% for all three conditions while the oxygen and nitrogen removal varied from 30 to 95%.

The H-Coal distillate was processed at 1500 psig and 2.9 space velocity for the mild severity run and at 2500 psig and 0.5 space velocity for the high severity run resulting in chemical hydrogen consumptions of 570 and 1730 SCF/Bbl respectively. The temperature was approximately 700°F for both runs. Again, sulfur removal was greater than 95% while oxygen and nitrogen removal varied from 40 to 99%.

The raw and hydrotreated H-Coal distillate were distilled to remove the material boiling below 350°F. These, together with the as received raw and hydrotreated SRC recycle solvent, were used as the test fuels for the combustion tests. Table 2 lists the chemical and physical properties of the coal liquid fuels. Also shown are the properties of the No. 2 petroleum fuel used in the combustion tests. In general, the coal liquids have lower API gravities; are higher boiling; and contain less hydrogen (i.e., more aromatic) and more sulfur, nitrogen, and oxygen than the petroleum fuel. The trace metal elements are significant in the raw SRC recycle solvent and H-Coal distillate; hydroprocessing reduces these metals to levels equivalent to the No. 2 petroleum fuel. The raw SRC recycle solvent contains only 7.4 wt % hydrogen with 74 % of the carbon atoms in aromatic ring structures while the raw H-Coal distillate contains 9.1 wt % hydrogen and 55% aromatic carbon. The most severely hydroprocessed SRC recycle solvent and H-Coal distillate still contain 34 and 27% aromatic carbon respectively compared to 19% aromatic carbon in the No. 2 petroleum fuel. In addition, severe hydroprocessing increased the heat of combustion of the coal liquids equivalent to that of No. 2 fuel.

3.2 TURBINE ENGINE SIMULATION RESULTS

3.2a) Fuel Forwarding and Atomization

Due to the small quantities of fuel available, the constant pressure recirculating fuel system designed for use with the test passage could not be used. Instead a small tank pressurized with nitrogen was used as a source of constant pressure fuel. The fuel nozzle assembly chosen for these tests was the conventional air assist atomizing type used regularly with No. 2 fuel in the combustion test passage. This type nozzle consists of an orifice and a conical swirl element which produces a rapid rotation of the oil within the conical swirl chamber. The air to assist in atomization is brought close to the orifice by an air swirler where it mixes with the oil in a highly turbulent manner. The air swirler is kept in place by a cap that goes over the whole assembly. A second cap is used to keep the nozzle cool and to obtain an air flow pattern at the head of the combustor similar to that in a full scale combustor.

Studies were conducted to determine whether the regular fuel nozzle assembly designed for flow rates of ten to thirty gallons per hour would give good atomization in the one to two gallons per hour range if smaller fuel nozzles were employed. The small scale fuel nozzles were mounted in a suitable enclosure in the laboratory and No. 2 fuel was pumped into the nozzle at a pressure of 100 psi. The spray pattern was observed visually and photographs were taken.

It was found that the degree of atomization was better than that observed with the larger nozzles. No individual droplets or drippings could be seen and when the atomizing air was turned on the spray was effectively atomized. From this test, it was concluded that the hollow cone spray pattern produced by the small scale nozzle was suitable for the coal liquid combustion studies.

3.2b) Combustion and Emission Characteristics

The complete results of the combustion tests on the seven coal derived fuels are tabulated in Table 3. This table also presents data for the base No. 2 petroleum fuel. This fuel was run prior to the combustion of each coal-derived liquid and the values reported in Table 3 represent an average for all base line runs.

SRC Recycle Solvent:

SRC recycle solvent (7.4 wt % H) was the first coal liquid tested. The transition from No. 2 fuel to the SRC recycle solvent was fairly smooth and steady-state conditions were easily established in the combustion test passage. The most significant change observed was the sharp increase in NO_x emissions from the base line fuel. However, after about an hour of testing it became evident that the combustor walls were not maintaining a uniform temperature and were showing signs of erratic temperature fluctuations. Based on these observations, it was speculated that coke deposition and burning was taking place on the combustor walls. A small increase in smoke number at the time of fuel transition was observed but it eventually declined to values less than those observed for the No. 2 fuel. Apart from the difference cited above no other major observations were noted during the first one and one-half hours of testing with the recycle solvent. However, after about one and one-half hours of running it became evident that the combustor had burned out. The test passage housing the combustor developed a dull red hot spot and the test was terminated after 1.6 hours of running. On opening the test passage and observing the damage it was noted that a large portion of the combustor dome and a section of the combustor wall had burned through. Coke deposits were found both on the combustor wall and at the nozzle. The combustor can before and after this test is shown in Figures 2A and 2B.

The second fuel tested was the most severely hydrotreated recycle solvent (11.0 wt % H) using a new combustor can identical to the one that was destroyed. The base line test conducted with this combustor using No. 2 fuel produced higher NO_x and UHC readings. However, such variations in combustor emission characteristics are not unusual especially after replacing combustors. The transition from No. 2 fuel to the coal liquid was made smoothly and the test was conducted with no problems. After the test, the combustor was opened and no evidence of any coke deposits were found. The combustor wall showed no heat distress effects and this test also yielded fairly low smoke numbers.

A moderately hydroprocessed recycle solvent (10.3 wt % H) was the third fuel tested. The initial attempt to switch from No. 2 fuel to this hydroprocessed liquid was not very successful. It was found soon after the transition that the combustor wall temperature rose appreciably. This necessitated termination of the experiment and disassembly of the passage to check the fuel nozzle assembly and combustor can for coke formation. It was found that the nozzle was fouled by a small carbon deposit. The can was relatively clean except for two small spots where coke had deposited. Evidently, a disruption of the fuel spray pattern by the carbon deposited on the nozzle was responsible for the increase in wall temperature observed.

After cleaning the nozzle and can, a second attempt was made using this fuel. This time the transition from No. 2 fuel to the moderately hydro-processed recycle solvent (10.3 wt % H) was successful and the run was made without any difficulty. The wall temperatures as well as the NO_x emissions were substantially higher with this coal liquid compared to No. 2 fuel. On the other hand, smoke was satisfactory. After the run, the test passage was opened and examined for deposits. Evidence of coking on the can wall was noticed. A large piece of coke was found on the last step of the can and another attached to the dome. Other carbon deposits were also found on the wall of the test passage. In addition, the nozzle had moderate coke deposition.

The cleaned nozzle and can were put back in the test passage and the fourth fuel, a mildly hydrotreated recycle solvent, (8.9 wt % H), was tested. The transition from No. 2 fuel to the coal liquid was made and no major problems were encountered during this run. However, it was found that during the course of the run the combustor wall temperature continually increased from an initial level of 1265°F to 1810°F. Smoke levels as well as NO_x levels were higher than with No. 2 fuel. On termination of the run, the test passage was disassembled and a large coke piece was found lying in the passage. Further examination revealed that it had been attached to the nozzle and probably came off at the time the fuel was turned off. The coke piece remaining on the nozzle is shown in Figure 3.

H-Coal Distillate:

The first H-Coal fuel tested was the severely hydrotreated product (11.7 wt % H). The base line test data using No. 2 fuel oil indicated the same order of emissions as for the previous base line tests. The transition from No. 2 fuel to the severely hydrotreated H-Coal distillate was relatively smooth and the test was completed with no problems. After the run, the test passage was opened and the combustor examined. No evidence of any coke deposits on either the combustor can or on the nozzle were found. The fact that this fuel was clean-burning is also evidenced by the low smoke numbers measured (Table 3). The mildly hydrotreated H-Coal product (10.5 wt % H) was the second H-Coal fuel tested. Initially, the combustor was fired with No. 2 fuel and the base line operating characteristics obtained. The transition to the coal liquid was relatively smooth. It was found on transition that both the combustor wall temperatures and NO_x emissions increased slightly and then gradually decreased over the run. Otherwise, no significant changes were observed. After the run, the test passage was opened up and again examined. No evidence of any coke buildup either on the combustor can or on the nozzle was found.

The cleaned nozzle and the can were put back in the test passage and the third H-Coal fuel, raw H-Coal distillate (9.1 wt % H), was tested. The passage was started on No. 2 fuel and base line data were taken. The changeover from No. 2 fuel to raw H-Coal distillate was made without any problems. However, it was found that during the initial part of the test run the combustor wall temperature was much higher than with No. 2 fuel. Therefore, in order to prevent the likelihood of any damage to the combustor can the latter part of the test run was completed at a reduced exhaust gas temperature. The measured NO_x levels were higher in comparison to the No. 2 fuel. On termination of the test, the test passage was disassembled and, through the combustor can was found to be free of coke deposits, a buildup of coke around the nozzle was observed.

Data Analysis:

Raw coal liquid fuels differ from petroleum-derived fuels in that they are very aromatic and, as such, are hydrogen deficient. Hydrotreating of these fuels consists of catalytically adding chemical hydrogen to the fuel. Hydrogenation also decreases both the heteroatom and aromatic content of the liquid. Hence, the hydrogen content of the coal liquids is an important parameter and it is used as an index of fuel quality in the presentation of most of the emission and combustion results presented below.

In Figure 4, the emissions of CO_2 , CO, UHC, NO_x and smoke are shown plotted against the weight percent hydrogen in the fuel. The CO_2 emissions (Figure 4A) in the exhaust do not show any appreciable trend with the hydrogen content of the fuel.

CO emissions, plotted in Figure 4B as a function of fuel hydrogen content, do not show any definite trend. However, the CO emissions are quite low and acceptable in spite of the small size of the combustor tested and the significant quenching effects observed under these conditions.

In Figure 4C, the unburned hydrocarbons are plotted as ppm of equivalent CH_4 in the dry exhaust gas. The emissions are again low and acceptable. The slight increase of UHC with increasing hydrogen content for the SRC derived fuels and not for the H-Coal derived fuels is probably due to the low boiling point constituents present in the former. These will tend to mix earlier and more rapidly with the cooling air and subsequently be quenched out. The quenching effect is increased due to the combustor wall temperature being lower with the high hydrogen fuels.

In Figure 4D, the NO_x emissions are shown plotted against hydrogen in the fuel. These emissions decrease with increased hydrogen content of the fuel. This is as would be expected, for with increased hydrogenation of the coal liquids, the bound nitrogen content is decreased leading to reduced NO_x in the exhaust. An average value of NO_x emissions for No. 2 fuel for all the base line tests is 148 ppm as shown by the data point for this fuel. Thus, it is apparent that in order to meet the EPA proposed rules regarding NO_x emissions increased denitrogenation of coal liquids is desirable from the turbine designers point of view. However, even for No. 2 fuel (0.008 wt % Nitrogen) it is not easy to meet this EPA rule and turbine designers are looking for and working on alternative combustion systems. For example, if the premixed combustor concept is developed then other parameters, i.e., evaporation time, ignition delay, etc. will become of overriding importance rather than NO_x emissions.

The average smoke number measured is displayed in Figure 4E. Although low smoke numbers were indicated it is speculated that they were not really that low for all of the fuels tested. The reason for this thought is that when the raw SRC recycle solvent (7.4 wt % H) was tested the smoke increased immediately after the transfer to the coal-derived liquid and then started to decrease. Large carbon particles were found on the passage walls, etc., and the line connecting the smoke meter to the passage was found heavily laden with soot. The line, therefore, could be filtering out the smoke particles. A similar sudden increase in smoke and subsequent decrease was also observed on switching to the mildly hydrotreated SRC recycle solvent. Thus, the lined out readings listed in Table 3 are suspect for the SRC recycle solvent fuels.

For the H-Coal test series, the smoke sampling line was replaced with a short line avoiding sharp bends (to avoid carbon or moisture separation and subsequent carbon deposition) from the passage to the smoke meter and a much higher flow rate was used. It was observed during these series of tests that the smoke numbers observed varied from 0 to 1 for both the H-Coal fuels and No. 2 fuel; as such the maximum value of 1.0 was plotted on Figure 4E for H-Coal fuels.

The relative NO_x measured with coal-derived fuels divided by the base line NO_x measured with No. 2 fuel is plotted in Figure 5 as a function of the nitrogen content of the fuel. It should be noted that the NO_x values observed for the severely hydrotreated SRC recycle solvent (11.0 wt % H) and H-Coal distillates (10.5 and 11.7 wt % H) are lower than or equivalent to No. 2 fuel even though the coal liquids have a slightly higher nitrogen content. In these cases, the contribution due to fuel bound nitrogen is more than compensated for by the reduced thermal NO_x production rate. This is in agreement with the lower exhaust temperatures observed for these fuels (compared to No. 2 fuel). The average combustor wall temperature was always higher using the coal-derived fuels as compared to No. 2 fuel. This is due to the higher thermal radiation from these fuels. A possible exception, as shown below, to the previous comment on combustor wall temperatures is the most severely hydroprocessed H-Coal fuel (11.7 wt % H).

In Figure 6A, the average combustor wall temperature for SRC derived fuels is plotted from fifteen minutes before switchover to coal fuels to the time that either the wall temperature was unacceptable or the fuel was exhausted. Curve A is for the raw recycle solvent (7.4 wt % H) and as can be seen the wall temperature increased by almost 100°F after transfer to the coal liquid. Over the first part of the test the wall temperature increased by almost 200°F to 1680°F as compared with an average gas temperature of 1800°F. It is speculated that at this point the combustor was destroyed since the wall temperature began to behave in an erratic manner. Finally, after about ninety minutes of operation the destruction of the combustor became obvious due to the presence of a hot spot on the passage wall.

Curve B is for the least severely hydrotreated recycle solvent (8.9 wt % H). On switchover from No. 2 oil a similar increase to that observed for the raw recycle solvent was noted. This was possibly due to the onset of coking. A sharp increase in wall temperature at the termination of the test was also noted.

Curve C in Figure 6A is the data point observed with the aborted test using the moderately hydrotreated recycle solvent (10.3 wt % H). The sudden increase in wall temperature is hard to explain except to say that in the fuel transfer process the spray nozzle pattern was disturbed. On cleaning the nozzle and mounting it back in the passage a satisfactory run (Curve D) was obtained. However, the lined-out average combustor wall temperature for this coal liquid was about 250°F hotter than with the base No. 2 fuel.

Curve E was obtained using the severely hydrotreated recycle solvent (11.0 wt % H). It appeared to run slightly lower than No. 2 fuel on transfer but after fifteen minutes into the run the temperature increased by almost 200°F.

In Figure 6B, average combustor wall temperature data for the H-Coal fuels are presented in a manner similar to that utilized for the SRC fuels. Curve A is for the severely hydrotreated H-Coal distillate (11.7 wt % H). This curve indicates that no significant change in the can wall temperature occurred when utilizing this fuel as compared to the No. 2 fuel. Curve B is for the mildly hydrotreated H-Coal distillate (10.5 wt % H). It was found that a gradual increase in wall temperature occurred subsequent to the transfer from No. 2 oil. During the course of the experiment, the average wall temperature ran about 200°F hotter. Curve C is for the raw H-Coal distillate (9.1 wt % H). Subsequent to transfer from No. 2 fuel to the coal liquid the average can temperature rose from approximately 1180°F to 1675°F. To avoid possible damage to the combustor can if operation was continued at this condition, the fuel flow was reduced until the can temperature was in the safe operating regime.

3.2c) Corrosion, Erosion and Deposition

A test period of one-three hours is too short to obtain quantitative information on the long-term corrosion, erosion and deposition effects with these stocks. However, limited information was obtained by exposing two test specimens (pins) of turbine alloys (In 792 and X45) to the combustion products from the raw SRC recycle solvent. After running approximately two hours the test was terminated and the pins were examined with a scanning electron microscope. Figures 7A and 7B show general scans (500x) of the surfaces with arrows indicating possible deposits. Iron, silica, alumina, calcium, phosphorous, copper and chlorine were all detected in these scans. Longer runs are needed to quantify the ultimate effects of these deposits on turbine life. However, the analyses of the raw coal liquids (Table 2) and the depositions observed on the test pins during the two hour test indicate that trace metals may be a problem in the utilization of coal liquids. Although no test pins were used for the hydroprocessed liquids in this study, the analyses indicate a significant decrease in the level of trace contaminants after hydroprocessing. This should contribute to a longer turbine life.

4.0 CONCLUSION

Combustion tests on raw distillate coal liquids from the H-Coal and SRC processes resulted in significantly higher NO_x emissions and increased combustor wall temperatures than with a comparable boiling range No. 2 petroleum fuel. In addition, both of the raw coal liquid fuels were high in trace metal contents which could lead to excessive corrosion, erosion, and deposition of turbine blades in long-term service. Hydroprocessing was effective in producing fuels of lower fuel bound nitrogen content, higher hydrogen (i.e., lower aromaticity), and in eliminating most of the detrimental trace metals. The resulting hydroprocessed coal liquid fuels gave lower NO_x emissions in the turbine combustor. Combustor wall temperatures decreased with increasing hydrogen content (i.e., higher hydroprocessing severity). The most severely hydroprocessed H-Coal liquid showed no increase in NO_x nor increase in combustor wall temperature compared to a base No. 2 petroleum fuel. However, the most severely hydroprocessed SRC recycle solvent, requiring the addition of 2800 SCF H_2/Bbl , gave slightly higher NO_x and higher combustor wall temperatures than the base petroleum fuel.

Specific conclusions based on the results of this work are:

- H-Coal distillate and SRC recycle solvent can be readily forwarded and atomized.
- In general, the combustion wall temperature is higher when burning coal liquids than for a base No. 2 petroleum fuel. Combustor wall temperature decreases with increasing hydrogen content of hydroprocessed coal liquid. The most severely hydroprocessed H-Coal distillate showed no increase in wall temperature over the base petroleum fuel. On the other extreme, the raw SRC recycle solvent (7.4 wt % hydrogen) caused burn-out of the combustor can in less than two hours.
- NO_x emissions were 30% higher for the raw SRC recycle solvent (0.62 wt % fuel bound nitrogen) compared to the base petroleum fuel (0.008 wt % fuel bound nitrogen). Increasing hydroprocessing severity decreased the fuel bound nitrogen content and produced fuels with NO_x emissions equivalent to the petroleum fuel.
- Coke formation on the fuel nozzle used in the combustor is a major concern with raw and mildly hydroprocessed coal liquids. These deposits ranged from massive for the raw SRC recycle solvent to nil for the most severely hydroprocessed SRC and H-Coal liquids. The severity of deposits in full scale combustors may be less due to their higher flow rates.
- Unburned hydrocarbons emissions are acceptable, increasing slightly with increasing fuel hydrogen. CO emissions are acceptable.
- Smoke emissions were low for H-Coal liquids. Reliable smoke numbers could not be obtained for the SRC recycle solvent due to possible soot and coke formation in the sample line.
- Flame temperatures were not significantly different for any of the fuels tested as determined by optical pyrometry.

ACKNOWLEDGMENT

The work was performed under EPRI Project RP 361-2, jointly sponsored by Electric Power Research Institute and Mobil Research and Development Corporation.

REFERENCES

- (1) White, J. W., Sprague, R., McGrew, W., editors "Clean Fuels from Coal - Symposium II Papers", Institute of Gas Technology, June 23-27, 1975.
- (2) Callen, R. B., Bendoraitis, J. G., Simpson, C. A., Voltz, S. E., Ind. Eng. Chem., Prod. Res. Dev., 15, 223 (1976).
- (3) Schiller, J. E., Hydrocarbon Processing, 56 (1), 147 (1977).

- (4) Cabal, A. V., Voltz, S. E., Stein, T. R., Ind. Eng. Chem., Prod. Res. Dev., 16, 58 (1977).
- (5) Haebig, J. E., Davis, B. E., Dzuna, E. R., Preprint Div. Fuel Chemistry, Am. Chem. Soc., 20 (1), 203 (1975).
- (6) Nowack, C. J., Solash, J., Delfosse, R. J.; paper presented at 82nd National Meeting of American Institute of Chemical Engineers, Synthetic Liquid Fuels, Paper No. 19b, Atlantic City, N. J., August 29-September 1, 1976.

Table 1

Hydroprocessing Conditions and Yields for Upgrading SRC Recycle Solvent and H-Coal Distillate

Coal Liquid	SRC Recycle Solvent				H-Coal Distillate		
	Feed	Mild	Moderate	Severe	Feed	Mild	Severe
Hydroprocessing Conditions:*							
Pressure, psig	-	2500	2500	2500	-	1500	2500
LHSV	-	2.9	0.8	0.4	-	2.9	0.5
Temperature, °F	-	678	711	718	-	697	702
H ₂ Consumption, SCF/Bbl	-	1140	2260	2800	-	570	1730
Yields, wt %							
Cl-C ₃ Gas	-	0.16	0.11	0.42	-	0.04	0.20
C ₄	-	0.22	0.07	0.22	-	0.01	0.10
C ₅	-	0.11	0.05	0.12	-	0.03	0.06
C ₆ + Liquid	-	98.90	98.34	98.05	-	99.60	100.21
H ₂ S	-	0.34	0.38	0.39	-	0.13	0.14
NH ₃	-	0.22	0.62	0.73	-	0.18	0.46
H ₂ O	-	1.72	3.73	4.17	-	0.90	1.58
Heteroatom Removal, wt %							
Sulfur	-	85	97	98	-	95	99
Oxygen	-	39	85	95	-	54	93
Nitrogen	-	30	83	96	-	40	99
Total Liquid Product Properties							
Gravity, °API	5.3	13.0	19.5	23.4	17.1	21.3	28.0
Hydrogen, wt %	7.4	8.9	10.3	11.0	9.8	10.6	12.2
Sulfur, wt %	0.37	0.06	0.01	0.01	0.13	0.007	<0.002
Nitrogen, wt %	0.62	0.44	0.11	0.02	0.38	0.23	0.005
Oxygen, wt %	3.9	2.4	0.6	0.2	1.5	0.7	<0.1

*Catalysts: American Cyanamid HDS-1441A (CoMo) for SRC Recycle Solvent and Ketjen 153S (NiMo) for H-Coal Distillate.

Table 2
Properties of Combustor Test Fuels

Fuel	Petroleum No. 2 Fuel Oil	SRC Recycle Solvent			H-Coal Distillate		
		Raw	Mild	Hydrotreated Moderate Severe	Raw	Mild	Severe
Sample No.	J8726	76D-1289	J8511	J8512	76D-3521	J8828	J8830
Elemental Composition, wt %							
Hydrogen	12.9	7.4	8.9	10.3	9.1	10.5	11.7
Sulfur	0.093	0.37	0.06	0.01	0.10	<0.002	<0.002
Nitrogen	0.008	0.62	0.44	0.11	0.39	0.12	0.04
Oxygen	<0.1	3.9	2.4	0.6	1.5	0.3	0.2
Trace							
Contaminants, ppm wt							
Titanium	<1	20	1	1	-	<1	<1
Sodium	0.55	0.39	1.1	0.08	0.59	0.36	0.36
Potassium	0.37	0.19	0.22	0.03	0.08	0.04	0.04
Calcium	0.17	0.35	0.23	0.12	0.14	0.01	0.01
Vanadium	<0.1	0.9	<0.1	0.2	0.1	0.1	0.1
Lead	-	0.9	0.9	0.6	< 1	< 1	< 1
Iron	0.2	61.0	2.3	1.5	10.3	5.7	3.6
Chloride	-	35.0	17.0	5.0	-	-	-
Properties							
Gravity, °API	33.6	5.3	13.0	19.5	14.7	18.8	23.2
Aromatic Carbon, %	19	74	66	46	55	42	27
Flash Point, °F	153	180	87	48	195	190	175
Heat of Combustion, BTU/lb	19500	16920	17730	18570	18080	18630	19040
KV, cs (at 100°F)	2.61	5.79	3.43	2.20	3.00	2.44	2.17
KV, cs (at 210°F)	1.09	1.48	1.10	0.93	-	-	1.06
Distillation, °F							
IBP	370	324	175	180	338	328	325
5%	412	375	303	216	366	357	352
10%	432	394	362	232	388	379	366
30%	474	446	413	402	406	402	396
50%	504	492	469	463	450	444	441
70%	540	564	534	525	503	493	485
90%	589	665	627	602	595	580	563
95%	611	709	681	649	659	632	609
BP	624	872	857	818	774	766	733

Table 3
Coal Liquids Combustion and Emission Results

Run No.	Fuel (wt % Hydrogen)	Air Flow, Lbs/Sec.	Fuel Flow, Lbs/Sec.	Atom. Air Flow, Lbs/Sec.	Comb. Press., psig	Inlet Temp., °F	Exhaust Temp., °F	Plane Temp., °F	Emissions				
									CO ₂ , %	CO, ppm	NO _x , ppm	UHC, ppm	Smoke No.
	Petroleum No. 2 (12.9)*	0.12	0.0036	0.0054	52.6	512	1814	3543	5.3	33	148	18	1.5
1	Raw SRC Recycle Solvent (7.4)	0.088	0.0035	0.003	51.0	608	1783	3452	5.8	21	191	4.4	1.2
2	Severely Hydroprocessed SRC Rec. Solvent (11.0)	0.12	0.0037	0.006	51.5	502	1764	3207	5.7	33	149	30	2.0
3	Moderately Hydroprocessed SRC Rec. Solv. (10.3)	0.12	0.0036	0.006	53.0	503	1752	3564	5.3	28	166	12	1.5
4	Mildly Hydroprocessed SRC Rec. Solv. (8.9)	0.10	0.0040	0.005	51.0	493	1786	3422	5.9	13	194	0.5	3.5
5	Severely Hydroprocessed H-Coal Distillate (11.7)	0.13	0.0035	0.006	53.1	500	1781	3543	5.5	31	134	7	<1
6	Mildly Hydroprocessed H-Coal Distillate (10.5)	0.13	0.0037	0.006	53.0	527	1721	3614	5.7	41	150	7	<1
7	Raw H-Coal Distillate (9.1)	0.11	0.0037	0.006	52.4	520	1696	3577	6.1	39	181	10	<1

*Average value for all base line tests.

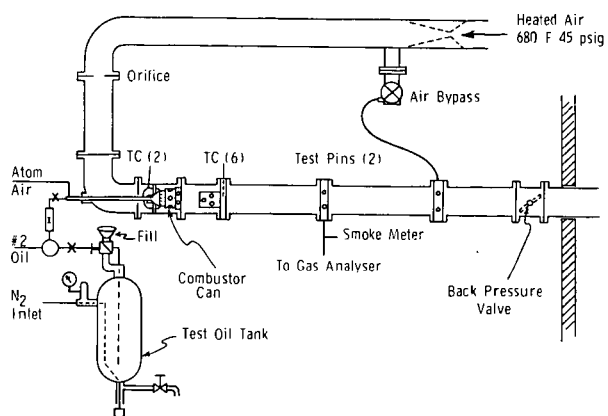


Figure 1. Combustor Test Passage



Figure 3. Coke Deposits on Fuel Nozzle Assembly After Test of Mildly Hydrotreated SRC Recycle Solvent (8.9 wt % Hydrogen)

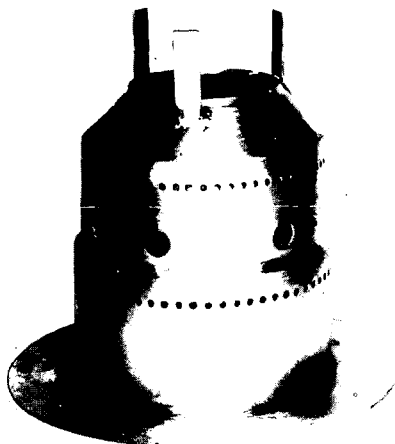


Figure 2a. Inconel X-750 Combustor Can Used for Combustion Tests

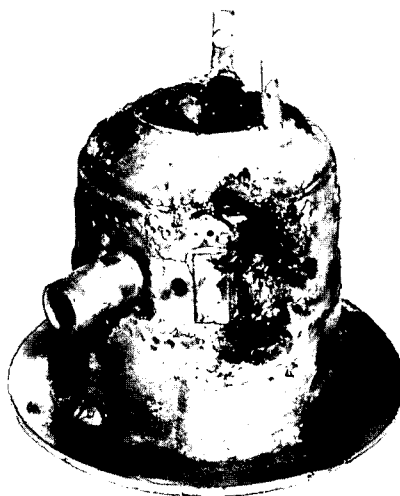
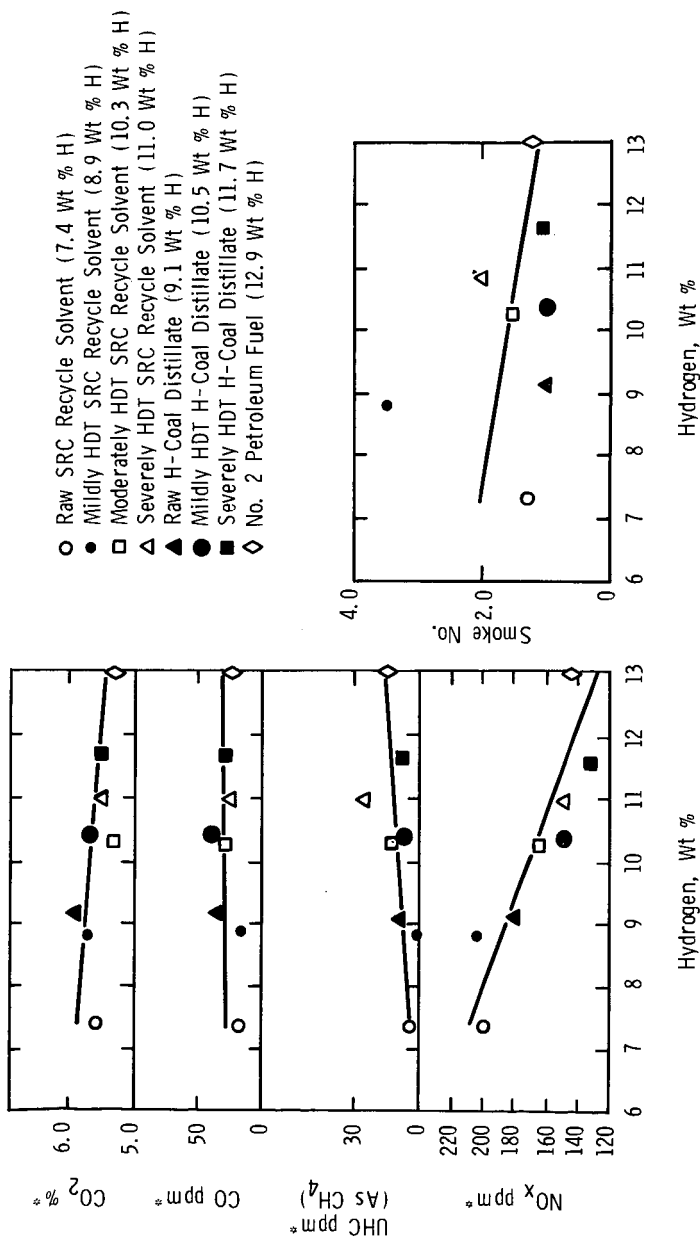


Figure 2b. Combustor Can (Side View) after Test of Raw SRC Recycle Solvent



* Based on Dry Volumetric Basis

Figure 4. Composition of Exhaust Gases as a Function of the Hydrogen Content of Fuels.

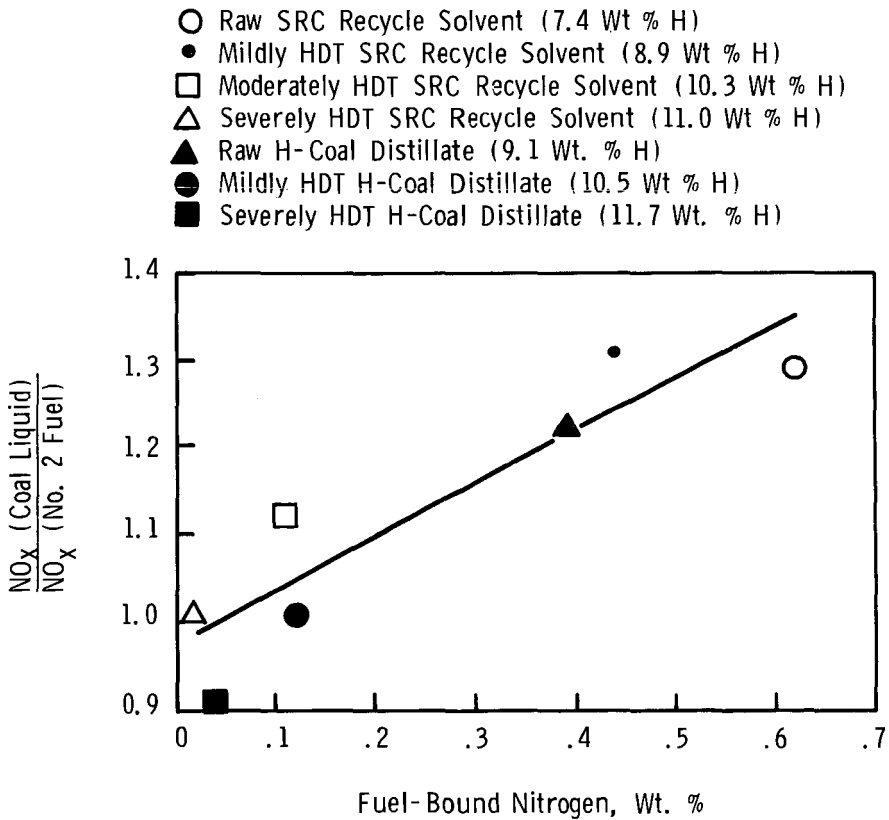


Figure 5. Relative NO_x Values as a Function of the Fuel-Bound Nitrogen Content of the Coal-Derived Fuels.

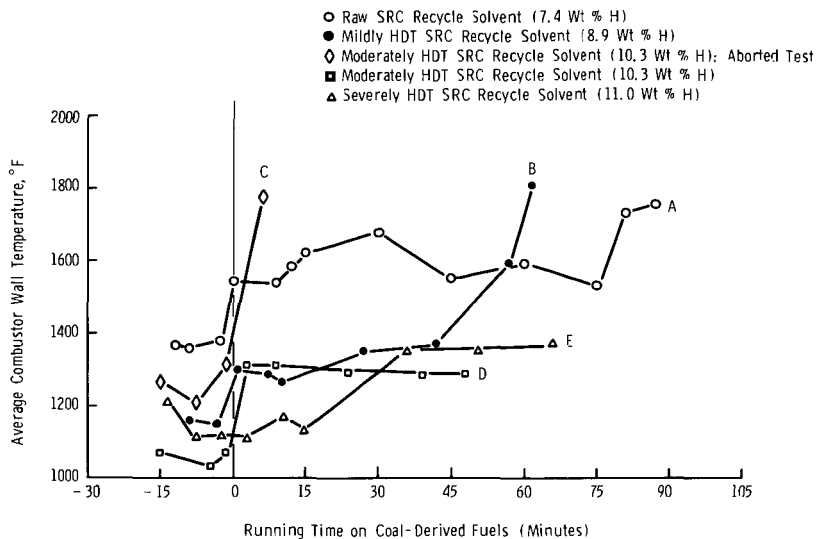


Figure 6A. Average Combustor Wall Temperature as a Function of Time for the SRC Recycle Solvent Fuels.

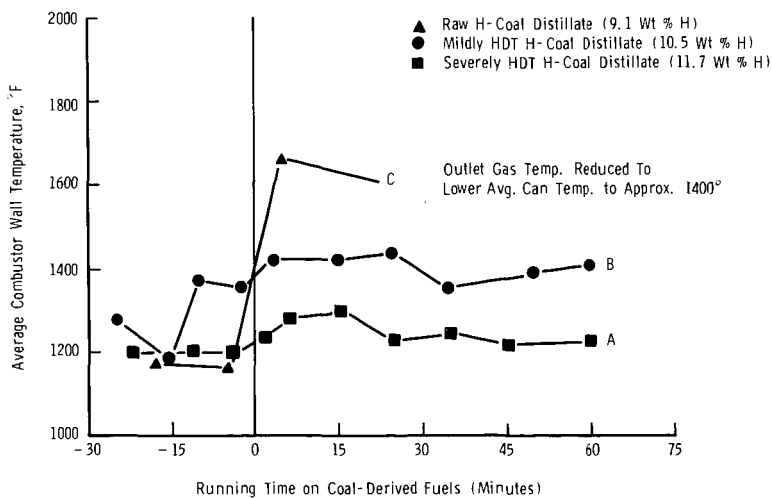


Figure 6B. Average Combustor Wall Temperature as a Function of Time for the H-Coal Fuels.

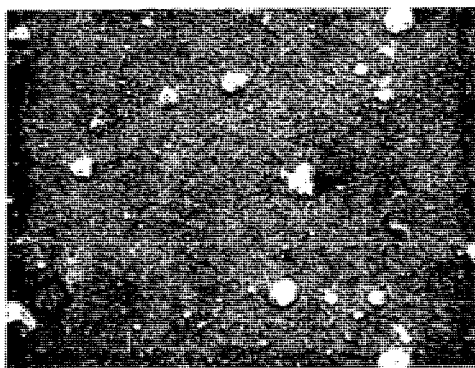


Figure 7a. General Scan of In 792 Surface (500X) Showing Surface Features and a Possible Deposit (Arrow)

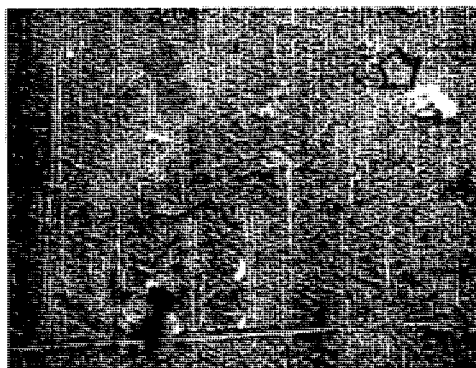


Figure 7b. General Scan of X45 Surface (500X) Showing Possible Deposit (Arrow)

COMBUSTION PROPERTIES OF COAL LIQUIDS FROM THE EXXON DONOR
SOLVENT PROCESS. C. W. Quinlan and C. W. Sigmund, Exxon
Research and Engineering Co., P. O. Box 4255, Baytown, Texas 77520

The Exxon Donor Solvent (EDS) Process converts bituminous, sub-bituminous and lignite coals into low sulfur liquid products. A brief description of the EDS process, the resulting liquid products and the flexibility of the EDS process to alter product distribution will be reviewed.

EDS liquid products produced from Illinois #6 bituminous coal were burned in a standard one gallon/hour home heating oil burner and a 50 HP industrial fuel oil boiler. Physical and chemical analyses and combustion emission data for both raw and hydrotreated coal liquids will be compared to conventional petroleum products.

Small Scale Evaluation of the Combustion
and Emission Characteristics of SRC Oil*

L. J. Muzio and J. K. Arand

KVB, Inc., 17332 Irvine Blvd., Tustin, CA 92680

INTRODUCTION

A potential alternate approach to the use of petroleum-based fuels in conventional combustion systems is liquid fuels derived from coal. In the present study, the combustion and emission characteristics of SRC fuel oil (a synthetic liquid fuel derived from coal) were evaluated in a laboratory boiler at a scale of 3 million Btu/hr. The facility was designed to simulate the combustion conditions found in large utility boilers. The synthetic liquid fuel was produced by the solvent refined coal process (1)** at the Department of Energy funded, and Gulf operated Solvent Refined Coal Pilot Plant.

The high nitrogen content (approximately 1% to 1.5% by weight) of the solvent refined coal oil (SRCO) is potentially a cause of high nitrogen oxides (NOx) emissions from conventional combustion systems. It is known that in the combustion of fuels containing chemically bound nitrogen, a fraction of this nitrogen combines with oxygen in the air to form nitrogen oxides which are emitted as pollutants in the flue gases. One percent by weight of nitrogen in a typical fuel oil has a potential of producing about 1,300 ppm (dry) of nitrogen oxides in boiler flue gases at 3% excess oxygen if all nitrogen in the fuel is converted to nitrogen oxides. For conventional combustion configurations, approximately 20% to 50% of the fuel nitrogen is converted to NOx with the percentage conversion decreasing as the nitrogen content of the fuel increases. Other variables such as excess air level and temperature play a lesser role (2,3). However, combustion modifications can be used to limit the conversion of fuel nitrogen to levels considerably less than the normally encountered 20% to 50%. These methods have been satisfactorily and repeatedly demonstrated on utility boilers. Additional nitrogen oxides are formed in high-temperature burner flame zones by oxidation of a small portion of the nitrogen in the combustion air.

The objective of this study was to document the combustion characteristics and the emissions of NOx, SOx, and particulates while burning SRC fuel oil in a boiler. In particular, the sensitivity of the emissions to load and excess air variations as well as air preheat, staged combustion, and flue gas recirculation were determined. These small scale test results can then be used to aid in assessing the performance of this fuel in a typical full scale utility boiler.

During the investigation, direct comparisons of the emission characteristics of the coal-derived fuel were made to those from a typical low-sulfur #6 fuel oil (0.24% nitrogen by weight) and a #2 oil with a nitrogen content of 0.024% by weight. Selected characteristics of the three fuel oils are shown in Table 1 along with the analysis of the western Kentucky coal from which the SRC oil was derived.

*Sponsored by Gulf Mineral Resources, Co., Denver, Colorado.

**Numbers in parentheses correspond to references at the end of the paper.

No attempt was made to explore the possible changes in storage and handling procedures which might be necessary to fire the coal-derived oil in a boiler originally equipped to fire residual, distillate oils or other fuels.

TABLE 1. TYPICAL FUEL CHARACTERISTICS

	Western Kentucky Coal	SRCO	#6 Oil	#2 Oil
C, wt %	72.2	86.6	86.61	86.82
H, wt %	5.0	8.38	12.25	12.69
N, wt %	1.4	1.12	0.24	0.024
S, wt %	3.6	0.26	0.28	0.11
Ash, wt %	10.5	0.008	0.016	0.003
O ₂ , wt % (by difference)	7.3	3.63	0.6	0.35
Gross Heat of Combustion, Btu/lb	13,150	17,040	19,150	19,190
API Gravity, 60 °F	--	8.3	2.3	32.3
Viscosity, SSU at 140 °F	--	35.6	324 (100°F)	34

APPARATUS

The basis of the combustion facility is a modified 80-HP firetube boiler which for these tests was fired at a rate of 3 million Btu/hr. The combustion modeling principles used in designing this facility to simulate combustion conditions in full scale utility boilers are discussed in Reference 4. The apparatus, shown in Figure 1, can be divided into five groups of components: (1) fuel supply, (2) air supply, (3) burner, (4) boiler furnace, and (5) instrumentation.

The oils were drawn from 55 gallon drums and delivered to the burner with a plunger type positive displacement metering pump. During tests with the #6 oil, the drums were heated to raise the oil to its pumping temperature and electrically heated to its firing temperature just upstream of the oil gun.

Air from an indirect-fired preheater passed through an insulated duct and a venturi meter to two valves which were then used to regulate the flow split between the burner air and second-stage air. For tests involving two-stage combustion, the second-stage air passed down an insulated duct, through another venturi meter, then to a perforated torus inside the combustion chamber. The secondary air was injected from this torus radially toward the axis of the combustion chamber through 32 orifices each 9/16" in diameter. Downstream of the burner air valve, the burner air flow was split into two ducts which enter the windbox from opposite sides. Recirculated flue gas, when used, was added to the combustion air upstream of the air preheater.

The burner used in this study was a scaled down version of a typical utility boiler oil burner. The burner utilizes a single 16-vane variable vane-angle air register for imparting swirl to the air flow. During these tests, the vanes were fixed at 20 deg. For the test results reported in this paper, a 30 deg. hollow cone mechanical type atomizer was used to deliver the oil to the combustion chamber. A more complete description of the burner can be found in Reference 5.

The boiler shell was an 80-HP Scotch dry-back type. At a firing rate of 3 million Btu/hr, the boiler's volumetric firing intensity was 38,500 Btu/hr-ft³, which is typical of oil-fired utility boilers. The steam produced by this boiler is vented at one atmosphere. Also, the laboratory boiler's combustion chamber was fitted with a stainless steel liner to give wall temperatures of about 800 °F, also typical of utility boilers.

The flue gas concentrations of NO , O_2 , CO , and SO_2 were analyzed continuously using a Thermo Electron Corp. chemiluminescent nitric oxide analyzer, a Beckman Model 742 oxygen electrolytic analyzer, an Horiba Model PIR2000 nondispersive infrared carbon monoxide analyzer, and a Dupont 411 photometric analyzer for sulfur dioxide. Smoke levels were determined using a Bacharach smoke tester (ASTM D2156-65) and reported as Bacharach smoke spot numbers, the scale of which consists of a series of ten spots from 0 to 9. Total particulate loadings were determined using EPA Method 5.

TEST RESULTS

The combustion and emission characteristics of the SRC oil were evaluated over a range of operating parameters typical of large utility boilers. With the exception of the variable air preheat tests, the test results reported were obtained at a nominal condition of 550 °F combustion air temperature and a firing rate of 3 million Btu/hr. Results will be presented for the following methods of controlling NO:

reduced excess air	fuel blending
staged combustion	ammonia injection
flue gas recirculation	water injection for smoke suppression
reduced air preheat	fuel additives for smoke suppression

The methods listed in the left-hand column above were investigated early in the testing. It was found that while the combustion modifications were effective in controlling nitric oxide, they were limited in their degree of effectiveness due to a tendency of the SRCO to smoke when the control methods were fully implemented. This greater tendency of the SRC oil to smoke than the other fuels tested is thought to be due to the high aromatic content of the coal-derived liquid.

The effect of excess air and staged combustion on the nitric oxide emissions for the SRCO along with the #6 and #2 oil are shown in Figure 2. The open symbols are single stage combustion and the closed symbols are two-stage combustion tests. During the staged combustion tests, the overall excess air level was maintained at 16% (3% overall excess O_2). Figure 2 shows that for single-stage combustion of SRCO, the NO produced is very sensitive to the excess air level and significantly higher than the NO emissions from the #6 and #2 oil. For two-stage combustion, the NO produced reached a minimum at about 80% A_B (A_B is the theoretical air at the burner and A_0 is the overall theoretical air; for single stage combustion, $A_B = A_0$), with further reductions in burner air flow resulting in an increase in the NO emissions. This effect has been observed by other investigators (6-9) and is attributed to NO formation during combustion in the second stage region.

When flue gas recirculation, at rates up to 20%*, was utilized in conjunction with staged combustion, no further reductions in the nitric oxide emissions were observed. Gas recirculation could be expected to have greater effect in boilers in which the heat release per unit area is very high. These units would tend to have higher contribution of thermal NOx, and the use of recirculation would tend to reduce the thermal NO more noticeably.

The effect of the combustion air temperature on the NO emissions is shown in Figure 3 for the SRCO during single stage combustion. This data shows there is a strong effect of the combustion air temperature on the NO emissions (approximately 9 ppm/25 °F, at 120% excess air) and that the sensitivity of the NO emissions to combustion air temperature increases with an increase in the excess air level.

*Mass of recirculated flue gas/sum of combustion air and fuel flow.

Fuel blending was also investigated as a means of firing the SRCO while limiting the NO and particulate emissions. The NO emissions from blends of SRCO and #6 oil are shown in Figure 4 for both single and two stage combustion.

The homogeneous gas phase reduction of NO by ammonia injection into the SRCO combustion products was also investigated during this study. The reductions in NO which were achieved were in agreement with those obtained and reported with other fuels (10).

Fully implementing the nitric oxide control techniques with the SRC oil, in particular staged combustion, was limited by the tendency of the oil to form high levels of smoke and particulates. This effect is illustrated in Figure 5 where the Bacharach smoke numbers for single stage and two stage firing of the SRCO and #6 oil are compared. During the two stage tests the stack gas oxygen concentration was maintained at 3% (dry basis). For single stage firing, the data in Figure 5 show that the SRCO tends to smoke more than the #6, note that even at 40% excess air ($A_B = 140\%$), a No. 2 smoke spot is obtained. Although for excess air levels above about 10% to 15%, the performance is acceptable in this unit. A striking difference in the performance in the two fuels is seen for two stage combustion conditions. The #6 oil produced a gradual increase in the flue gas smoke level as the first stage was operated more fuel-rich. With the SRCO, large increases in the stack smoke levels were obtained even at moderate staging conditions; a smoke number of 9 was obtained when the burner was operated at $A_B = 102\%$. This smoking tendency is suspected to be a consequence of the high aromatic content of the SRCO which is on the order of about 60% based on the carbon-to-hydrogen ratio.

This trade-off in NO and particulate emissions is further illustrated in Figure 6. These results show that in this particular system, staged combustion cannot be used to reduce the NO emissions below the 1974 EPA New Source Performance Standards (NSPS) without exceeding the 1974 NSPS particulate standard. A similar situation will likely exist in a full size unit although, quantitatively, the trade-off may differ from the laboratory scale results.

A number of methods were tested to limit the smoke and particulate formation while implementing staged combustion with the SRCO. These included steam atomization instead of mechanical atomization, water injection into the combustion air, and the use of combustion improving fuel additives (alkali and manganese based).

In this unit the NO and smoke levels were similar for both steam atomization and mechanical atomization. Utilizing water injection into the combustion air (at a rate equal to 7% of the oil flow, volumetric basis) along with staged combustion, the nitric oxide emissions could be reduced to about 260 ppm prior to the onset of smoking. This is about 40 ppm lower than the levels previously obtained with staged combustion alone.

Fuel additives have been used with varying degrees of effectiveness to control smoke emissions from combustion systems. A recent study by Battelle (11) has shown certain additives to be effective in reducing smoke with single stage firing of #6 and #2 oil although the additives may result in an increase of total particulate loadings.

During the present study, various additives were used with the SRCO while firing in a staged combustion mode. The additives chosen for evaluation were: barium naphthenate, calcium naphthenate, and CI-2 (Ethyl Corp. proprietary, manganese based). The naphthenates produced the best results in the Battelle study (11), with CI-2 being less effective. In the present tests, the additive concentrations ranged from 50 to 350 ppm of the primary metal in the oil.

All three additives altered the smoking characteristics of the SRCO with both single stage and two stage combustion. However, the manganese-based additive was most effective in achieving low NO emissions (e.g., lower A_B at the burner). It was also found that the naphthenates altered the NO formation as well as the smoke formation. As a result, the NO emissions with staging were approximately 30 to 50 ppm higher than for the base condition without the naphthenate additive.

Particulate loadings were determined while operating under staged combustion conditions with the manganese-based additive (CI-2). The results of these tests are presented in Table 2.

TABLE 2. PARTICULATES AND NO EMISSIONS
WITH SRCO AND CI-2 ADDITIVE

Test No.	1	2	3	4
Additive Concentration (ppm manganese)	0	0	0	345
A_0 Total Air, % Theor.	114.0	117.1	119.0	112.9
A_B Burner Air, % Theor.	114.0	103.0	83.0	77.0
Excess O_2 , % dry	2.7	3.2	3.5	2.5
CO, ppm dry	35	35	135	40
NO, ppm dry (corr to 3% O_2)	467	344	231	226
Smoke Number	0	3	< 9	8.5
Particulates, lb/MBtu	0.016	0.0168	0.344	0.068

As seen in Table 2, the additive was effective in limiting the particulate emissions during staged combustion. Also, the high particulate emission during Test No. 3 (staged combustion without the fuel additive) is due to carbon formation. Further, the amount of particulate contributed by the additive during Test No. 4 is apparently small. Based on the manganese content in the oil, the manganese would be expected to contribute to the particulates on the order of $0.014 \text{ lb}/10^6 \text{ Btu}$. The ash in the fuel contributes at most $0.004 \text{ lb}/\text{MBtu}$ to the flue gas particulate loading. It appears that the smoke emissions of the SRCO can be controlled on a larger unit with a fuel additive such as CI-2 when two stage or off-stoichiometric firing is used to reduce the nitric oxide emissions. It should be pointed out that tests were not conducted to determine the minimum additive concentration necessary to prevent smoke formation.

In general, the solvent refined coal oil appears to be a useful boiler fuel but its high nitrogen content dictates the need for applying NO control techniques to the system.

Since the SRCO is a very good solvent, compatibility of the oil with typical seals, O-rings, etc, used in boiler applications needs to be investigated.

The major problems encountered with the SRCO during this study were the high NOx emissions without NOx control methods coupled with the smoking tendency upon implementation of combustion modifications for NOx control. However, these small

scale tests show that control techniques are effective in reducing the NO_x emissions. The carbon monoxide emissions were also found to be low during the tests and the SO₂ emissions were within the expected range based on the low-sulfur content of the SRCO.

In the laboratory tests, variables such as the location of second stage air addition, atomizer design, air swirl setting, etc. were not fully investigated. With a more extensive effort, lower NO_x levels than demonstrated in this study may be possible on many large scale boilers. In addition, low NO_x designs for boilers and burners may be expected to further aid in minimizing NO emissions from the combustion of the SRC oil.

CONCLUSIONS

The following specific conclusions can be drawn from the results of these small scale tests:

1. The combustion performance of the solvent refined coal oil is equivalent to that of typical utility type fuel oils. It is volatile (similar to #2 oil) and does not require preheating to achieve an acceptable viscosity for pumping or atomization.
2. Potential problems with furnace slagging and metal wastage occasionally encountered with coal combustion should be negligible with SRCO because of its low sulfur and ash contents.
3. Nitric oxide emissions could be maintained at about 0.4 lb/10⁶ Btu for the SRCO utilizing combustion conditions typical of many large utility boilers. This was accomplished with two-stage combustion and 3% excess oxygen in the flue gas. At this condition, low stack gas concentrations of carbon monoxide and particulates were maintained.
4. Nitric oxide emissions could be reduced below 0.3 lb/10⁶ Btu for the SRCO by
 - (1) blending the SRCO with other petroleum-based fuel oils having much lower fuel nitrogen and then firing with two stage combustion, or
 - (2) using a fuel additive containing manganese and then firing with two stage combustion.Acceptably low stack gas concentrations of carbon monoxide, smoke, and particulates were obtained.
5. Air preheat has a significant effect on the NO_x emissions while firing SRCO.

REFERENCES

1. Schmid, D. K. and Jackson, D. M., "Recycle SRC Processing for Liquid and Solid Fuel," presented at the 4th Annual Interim Conference on Coal Gasification, Liquefaction, and Conversion to Electricity, University of Pittsburgh, Pittsburgh, PA, August 2-4, 1977.
2. Martin, G. B. and Berkau, E. E., "An Investigation of the Conversion of Various Fuel Nitrogen Compounds to Nitrogen Oxides in Oil Combustion," presented at the AIChE Meeting, Atlantic City, NJ, August 30, 1971.
3. Dzuna, G. R., "Combustion Tests on Shale Oil Fuels", presented at Central States Section/The Combustion Institute, April 1976.
4. Quan, V. et al., "Analytic Scaling of Flowfield and Nitric Oxide in Combustors," paper presented at EPA Pulverized Coal Combustion Seminar, June 1973.

5. Finney, C. S. and Sotter, J. G., "Pyrolytic Oil from Tree Bark: Its Production and Combustion Properties," AICHE Symposium Series No. 146, Vol. 71, June 1974.
6. Brown, R. A., Mason, H. B., Pershing, D. W., and Wendt, J.O.L., "Investigation of First and Second Stage Variables on Control of NO_x Emissions in a Pulverized Coal Furnace," presented at the 83rd National Meeting, AICHE, Houston, Texas, March 1977.
7. Pershing, D. W., Lee, J., and Wendt, J.O.L., "Fate of Coal Nitrogen Under Fuel Rich and Staged Combustion Conditions," presented at 70th Annual AICHE Meeting, New York, November 13-17, 1977.
8. Tenner, A. R., "Method and Apparatus for Reducing NO_x from Furnaces," United States Patent 4,021,186, May 3, 1977.
9. Arand, J. K., "Reduction of NO_x Through Staged Combustion in Combined Cycle Supplemental Boilers, Vol. II," EPRI Report 224, February 1975.
10. Muzio, L. J., Arand, J. K., and Teixeira, D. P., "Gas Phase Decomposition of Nitric Oxide in Combustion Products," Sixteenth Symposium (International) on Combustion, p. 199, The Combustion Institute, 1976.
11. Giammar, R. D. et al., "Experimental Evaluation of Fuel Oil Additives for Reducing Emissions and Increasing Efficiency of Boilers," FEA, PB 264 065, January 1977.

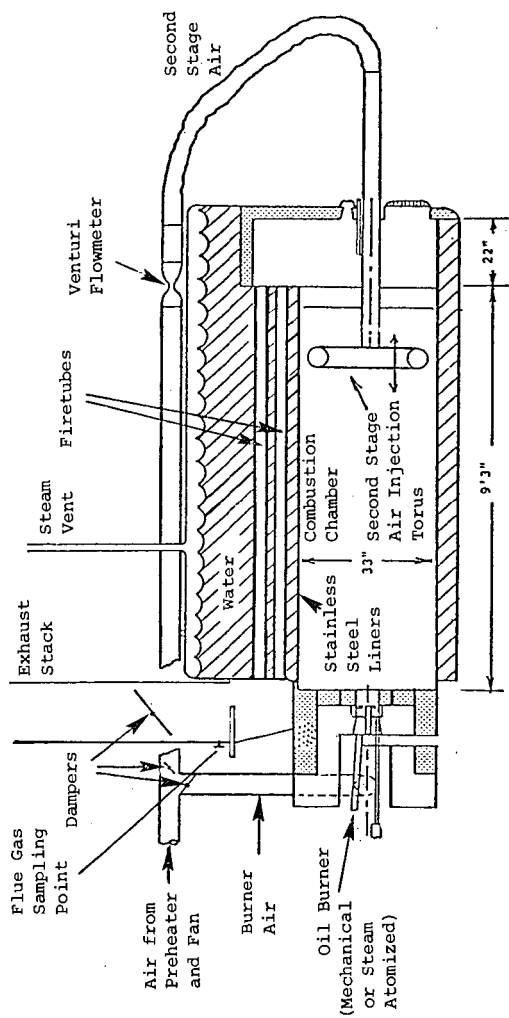


Figure 1. Schematic of 80 horsepower boiler.

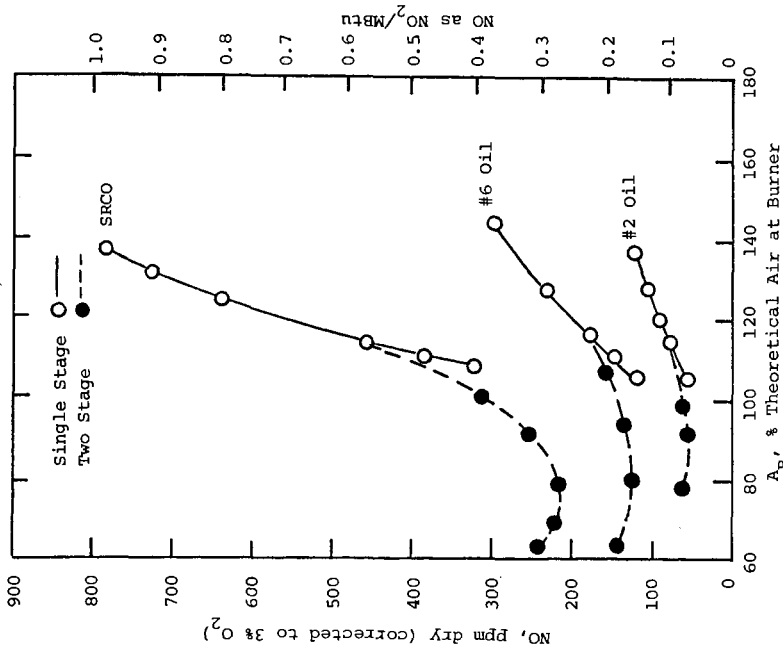


Figure 2. NO_x emissions from SRCO, #6 oil, and #2 oil (single-stage and two-stage combustion).

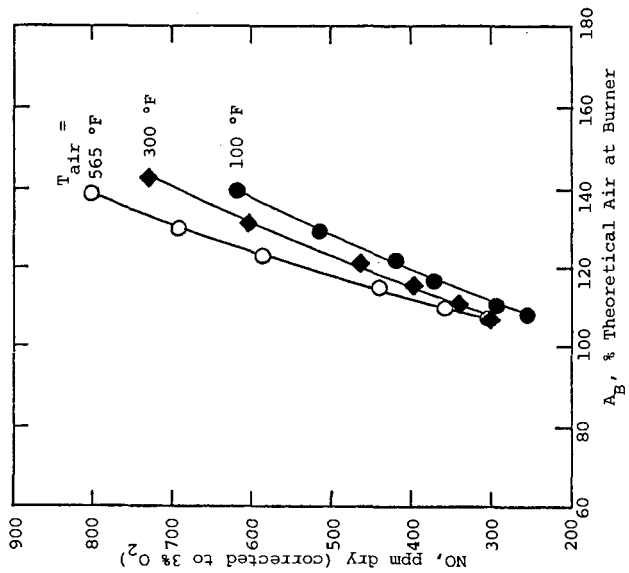


Figure 3. Effect of air preheat on NO_x emissions from SRCO; single stage combustion.

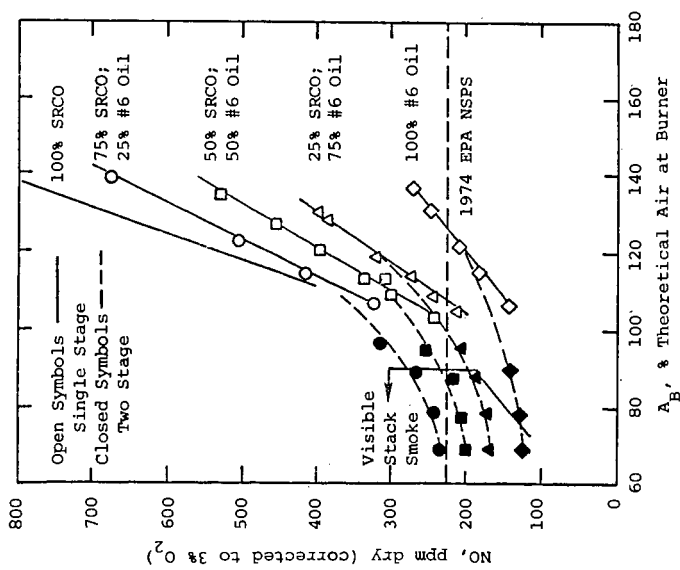


Figure 4. NO emissions from blends of SRCO and #6 oil.

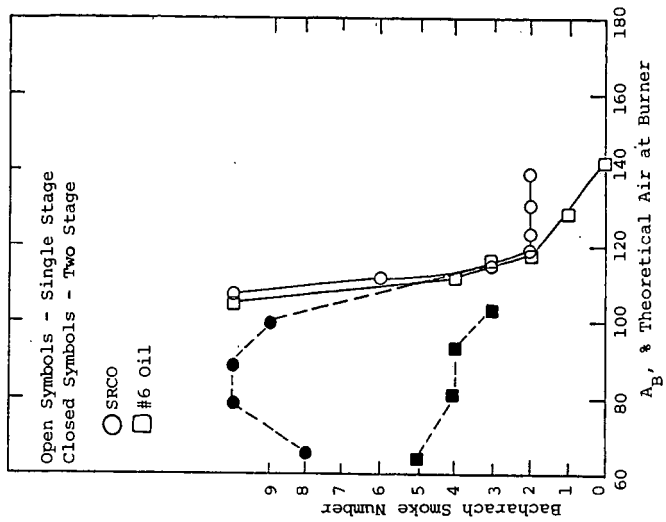


Figure 5. Smoke levels for SRCO and #6 oil.

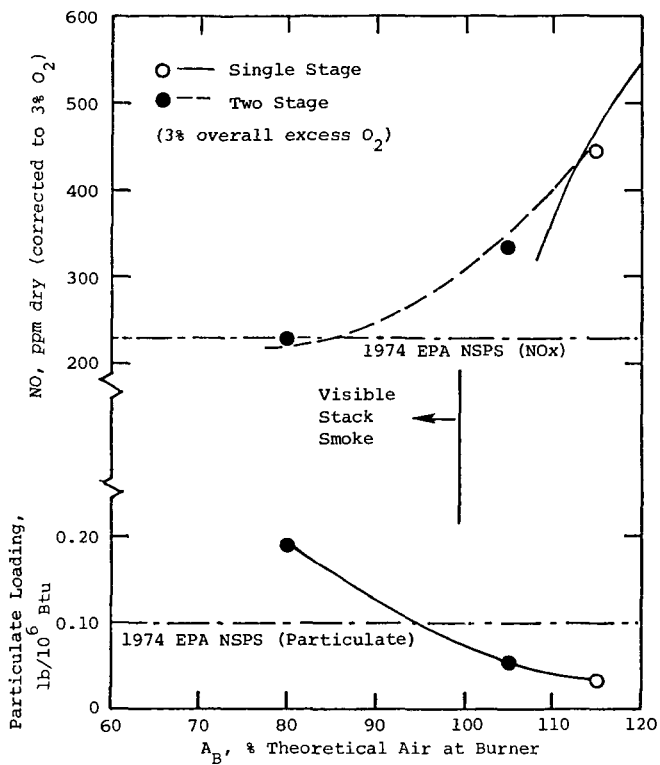


Figure 6. Particulate and NO emissions - SRCO.

Correlation of Fuel Nitrogen Conversion
to NOx During the Combustion of
Shale Oil Blends in a Utility Boiler

by

M. N. Mansour* and Melvin Gerstein**

In an oil fired utility boiler, nitric oxides are formed by two basic mechanisms; the thermal fixation of atmospheric nitrogen at elevated temperature within the flame zone, and the conversion of organically bound nitrogen in the fuel to NOx during the combustion process. NOx formation by thermal fixation, normally referred to as thermal NOx is essentially dependent upon flame temperature and concentration of oxygen and atmospheric nitrogen within the flame zone. The conversion of organically bound nitrogen to NOx, is directly related however, to the nitrogen content of the fuel.

Research on the reduction of nitrogen oxides produced from the reaction of atmospheric oxygen and nitrogen has been in progress for many years. More recently, attention has been given to the formation of nitrogen oxides from nitrogen compounds contained within the fuel. This source of nitrogen oxides becomes increasingly important as high nitrogen content fuels derived from shale and coal grow in use.

Recently, combustion tests have been conducted by Southern California Edison Company to evaluate NOx emission characteristics of shale oil (0.7% sulfur and 2% nitrogen) when burned in a utility boiler. The tests were conducted in a 45 MW Combustion Engineering boiler equipped with six

* Southern California Edison Company, P.O. Box 800, Rosemead, California 91770

** University of Southern California, School of Engineering, Mechanical Engineering Department, Los Angeles, California 90007.

face mounted oil burners each rated at 85 million Btu/hr. To comply with Air Quality Management District fuel sulfur content requirements shale oil was blended with low sulfur oil so that the average sulfur content of the fuel blend did not exceed 0.5%. Nitrogen content of the low sulfur fuel ranged between 0.2-0.25%. The NO_x emission was evaluated when burning shale oil blends using both conventional and off-stoichiometric modes of combustion. The emission levels were determined for a developmental low NO_x burner (LNB) and a conventional mechanical atomizing Peabody type burner.

As one might expect, NO_x emission level increased as the quantity of shale derived oil in the blend was increased. The incremental increase in NO_x emission level was proportional to the shale oil blending ratio which suggested that the increase in emissions was mainly caused by the high nitrogen concentration within the fuel. It was surprising to note, however, that the conversion efficiency of fuel nitrogen into NO_x decreased, as shown in figure 1, as the fraction of shale oil (and fuel bound nitrogen) increased. It was also found that changing burner stoichiometry from fuel lean to rich achieved a substantial reduction in fuel nitrogen conversion rate, particularly in the case of the Peabody burner.

While a number of explanations can be offered to such result, it is felt that the reduction in nitrogen conversion efficiency illustrated in figure 1 appears to be the result of two competing processes. (a) The formation of NO_x which increases as the nitrogen

containing shale oil content increases, and (b) the reduction of NOx by its reaction with high boiling hydrocarbons introduced with the shale oil and which is later released in the combustion process. The proposed model suggests that NOx is reduced after it is formed - a technique quite different from the classical approaches of slowing down NOx production by reducing the reaction temperature. The model assumes that the first process is a first order reaction with respect to fuel bound nitrogen and hence to the concentration of shale oil. The reduction process, however, is a second order reaction depending upon both NOx and the shale oil concentration, where the later term determines the residual hydrocarbon released late in the process. On this basis, the relative rate of NOx production would be given by:

$$\begin{aligned} \frac{1}{\text{NOx}} \frac{d(\text{NOx})}{dt} &= k_1 (\text{shale oil}) - k_2 (\text{NOx}) (\text{shale oil}) \\ \text{or } \frac{d(\text{NOx})}{\text{NOx}(\text{shale oil})} &= [k_1 - k_2 (\text{NOx})] dt \end{aligned}$$

A plot of $\frac{(\text{NOx})}{(\text{NOx})(\text{shale oil})}$ vs. (NOx) should be linear for equal residence times t . Such a plot is illustrated in figure 2 where a good correlation results.

The mechanism suggested here can lead to a general technique for reducing NOx formation by proper fuel blending. Burner design parameters could be also selected to enhance this delayed fuel vaporization while maintaining good burner flame stability. The

delayed vaporization of fuel, achieved through the use of high boiling temperature hydrocarbons or through optimization of burner design will then reduce NOx generated during the early phase of the combustion process. The concept is quite consistent with the general concept of staged combustion except that staging is accomplished by the natural separation processes occurring during fuel evaporation.

-
- * Southern California Edison Company
P. O. Box 800, Rosemead, California 91770
 - ** University of Southern California,
School of Engineering, Mechanical Engineering
Department, Los Angeles, California 90007

1d14b

R & D ON COMBUSTION OF SOLVENT REFINED COAL. W. Downs, C. L. Wagoner,
and R. C. Carr. Electric Power Research Institute, 3412 Hillview Ave.,
Palo Alto, Calif. 94305

The technical research for transportation, preparation, and combustion
of solvent refined coal that was performed by the Babcock and Wilcox Co.,
and Combustion Engineering to permit this new fuel to be utilized in a
utility boiler will be presented.

BURNING SOLVENT REFINED COAL. Richard D. McRanie, Southern Company Services, Inc.
Birmingham, Alabama 35202

Three thousand tons of solvent refined coal (SRC), manufactured at a Pittsburg & Midway plant in Tacoma, Washington, were successfully shipped to and burned in a Georgia Power Company 22.5 MW coal-fired utility boiler. The test demonstrated that SRC can be shipped in standard, open coal cars when treated with a commercially available coating spray to minimize blowing losses. Dust created in the conveyor system while loading and unloading the SRC can be controlled with a wetting agent spray. SRC was stored, pulverized, and burned with only minor modifications to existing power plant equipment. No modifications were necessary to the coal conveying equipment or the coal storage bunkers. The pulverizers were modified only to the extent that cold primary air was used and ball spring pressure was reduced. The only boiler modification was the installation of water-cooled, dual register burners. Emissions tests were performed while burning SRC and demonstrated that SRC is an acceptable fuel for meeting current EPA New Source Performance Standards for SO_2 and NO_x . The particulate emissions were greater than anticipated due largely to unburned carbon, a common problem with boilers of this vintage (1946). The particulate problem can be handled with a modern precipitator. Boiler efficiency tests were performed and indicate that efficiency when burning SRC is essentially the same as when burning coal. SRC was shown to be an exceptional boiler fuel from an operating standpoint. Soot-blowers, which normally have to be used 6-12 times a day, were not used at all during the 18-day test burn. The amount of flyash and bottom ash is significantly reduced. This will reduce ash system operating time and maintenance. The fact that SRC is brittle and easy to pulverize should reduce pulverizer maintenance.